Re-Design of a Hydraulic Oil Delivery System for Wind Turbine Blade Fatigue Testing

James Stack

Office of Science, Energy Research Undergraduate Laboratory Fellowship (ERULF)

Bucknell University

National Renewable Energy Laboratory

Golden, Colorado

August 10, 2001

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Energy Research Undergraduate Laboratory Fellowship under the direction of Walter Musial at the National Renewable Energy Laboratory.

Participant: ______________________________
James A. Stack

Research Advisor: ______________________________
Walter Musial

Table of Contents

Abstract

Re-Design of a Hydraulic Oil Delivery System for Wind Turbine Blade Fatigue Testing. JAMES STACK (Bucknell University, Lewisburg, PA 17837). Walter Musial (National Renewable Energy Laboratory, Golden, Colorado 80401).

The advancement of the wind energy industry is very much dependant on the ability to test the equipment being used in order to learn about their properties and make improvements in future designs. One type of test commonly performed is a fatigue test, which involves using hydraulic actuators to simulate the cumulative loading a blade will experience during its lifetime. Currently, new larger wind turbines are being produced with rotor blades spanning over 80 m which are stretching the testing capabilities of many test facilities. The Industrial User Facility at the National Wind Technology Center in Colorado is the premier wind turbine structural testing facility in the country and has just received a set of these new large-scale blades to test. But in order to maintain the speed at which these tests can be performed, the oil-pumping capacity of the hydraulic delivery system must be upgraded substantially, from the current rate of about 150 GPM up to 280 GPM. This paper focuses on the re-design of the hydraulics delivery system at the IUF, which involves combining two large pumps to operate in parallel, as well as the installation of a new oil cooler and larger piping to deliver the increased oil flow to the actuators in the test section.

Category: Engineering

School Author Attends: Bucknell University
DOE National Laboratory Attended: National Renewable Energy Laboratory
Mentor’s Name: Walter Musial
Phone: (303) 384-6956
e-mail Address: walter_musial@nrel.gov

Presenter's Name: James Stack
Mailing Address: 10101 Clearspring Road
City/State/ZIP: Damascus, MD 20872
Phone: (301) 253-1026
e-mail Address: james_stack@nrel.gov

- **Introduction**

As the past several months have clearly shown, the lives of many people in the world are greatly impacted by the fates and fortunes of the energy industry. Although many people in industrialized countries like the United States have come to take it for granted, the availability of cheap, reliable, and convenient electrical power is an essential part of modern life. However, as those in California can attest, the supply of energy on which we rely is not an infinite resource and does adhere to the same laws of supply and demand that all other consumer goods do.

With that in mind, it is instructive to look at where this energy actually comes from. In 1995, the United States received 84.5% of its total energy from fossil fuels (petroleum, coal, and natural gas) [1]. And while this great reliance on a finite supply of these dirty, greenhouse gas-emitting fuels is alarming enough, what is even more disconcerting is that a large proportion of this energy must be imported from other countries. (For instance, foreign oil accounts for 56% of all petroleum used in the country right now [1].)

Many people have suggested recently that, in addition to conservation and additional fossil fuel exploration, one way to potentially stabilize the country's energy supply and ensure its long-term sustainability is to make greater use of renewable energy (such as wind, solar, hydroelectric, biomass, and geothermal). Not only do these resources have the advantage of being exceptionally clean and good for the environment, but they are also virtually inexhaustible. Furthermore, they have the potential to more than meet the current energy demands of the people in the United States and the world. For instance, while the U.S. received only 7.5% of its energy from renewable resources in

1995 [1], the Department of Energy has estimated that wind energy alone could provide more than ten times the world's total energy demand [2].

At the moment, the primary obstacles to the widespread use and acceptance of wind energy and other renewable resources are economic factors. Due to the tremendous head start they have received, fossil fuels currently have a very well established infrastructure, thus making them the less expensive, more viable energy option for most people. That, however, is rapidly changing as more time and money are spent researching ways to make better use of renewable energy. For example, the cost of wind-generated electricity currently stands at around $.04 - $.06/kWh which is down significantly from about $.30/kWh in 1980 [3] and nearly on par with the $.02 - .03/kWh cost of conventional fossil fuel generated electricity [4].

With wind turbines, there is obviously no cost for the "fuel" that drives the device, thus the only real cost associated with this type of energy (aside from occasional maintenance work) is for the initial construction and installation of the turbines. Once installed and on-line, these machines can operate for an extremely long time (typically 20 to 25 years [5]) at virtually no cost to the owner. Obviously then, the easiest ways to lower the cost of wind energy and make it more competitive are to bring the construction and installation costs down (perhaps through government subsidies), to make the machines operate more efficiently, or to extend their operating lifetimes. While there is currently a great deal of work being done in each of these areas in order to improve the performance and competitiveness of wind energy, this paper focuses primarily on the last of the three ideas—developing wind turbines that last longer before they need to be replaced or repaired.

- **Wind Turbine Structural Testing**

The purpose of structural testing with wind turbines is to develop components that are stronger and will last longer under the intense, volatile conditions that wind turbines must endure over the course of their lifetimes. A number of different types of structural tests are commonly performed on wind turbine blades: ultimate static strength tests, photoelastic stress tests, modal tests, acoustic tests, and fatigue tests. By studying the structural properties of the blades, researchers are able to determine how (and when) a blade is likely to fail, and to evaluate the various design assumptions they have made and manufacturing techniques they have employed. As new generations of larger and larger wind turbine blades are produced using cheaper and lighter materials, it becomes crucial to test these new models to verify that they are structurally sound and to aid in the design of future generations of blades.

Probably the most common and most useful of these tests, fatigue testing is done to ensure that the blade is capable of sustaining the full spectrum of loads it will experience in its lifetime. For a typical wind turbine, this may amount to more than 5 million load cycles of varying amplitude and direction [6]. Fatigue testing thus attempts to simulate the cumulative effects of this wear in an accelerated manner by increasing the magnitude and frequency of the applied loads. In the U.S., these loads are typically applied to the test blades through a closed-loop servo-hydraulic system, where high pressure hydraulic oil is pumped to linear actuators that deflect the blades a specified distance. However, with the current generation of multi-megawatt wind turbines utilizing rotor blades with diameters up to 80 m, the equipment required to test these components can be quite massive. Also, the process can take quite a long time—in order to simulate 20 years of field life, a blade may have to be actuated for over three months [6].

- **The National Wind Technology Center's Industrial User Facility**

The Industrial User Facility (IUF) at the National Wind Technology Center (NWTC) in Colorado has been operating since 1996 and is this country's premier wind turbine structural testing facility. Wind industry engineers from all over the United States frequently bring their new turbine blades and other components to the IUF in order to test them using these state of the art facilities. But at the present time, the technology behind wind energy is growing at a tremendous rate, with bigger and bigger blades being produced, and the IUF is about to begin testing the latest generation of rotor blades, which measure up to 34 m in length. In order to maintain the speed at which these tests are performed, the frequency at which the blades are oscillated will have to be increased significantly (up from about 0.2 Hz to 0.76 Hz), which will necessitate a substantial upgrade in the current hydraulics system, effectively doubling the oil flow capacity and cooling capacity. Thus the purpose of this current project is to upgrade the fatigue testing capabilities at the IUF, allowing these new large-scale blades to be tested in a timely manner and maintaining the facility's status at the fore of the U.S. wind industry. This expansion project will require joining two existing pumps together to operate in tandem, installing at least one new oil cooler to operate in parallel with the existing one, resizing pipes for higher flow rates, and specifying and purchasing all of the necessary parts.

- **Hydraulics System Upgrade**

In the present arrangement, an MTS 505.150 Hydraulic Power Unit (see Figure 1) pumps oil to the actuators at a rate of 150 gallons per minute (GPM) at 3000 psi. This pump, which is located in the hydraulics room adjacent to the High Bay testing facility (see Figure 2) is connected to the actuators via a 2” OD Pressure line, and a 2 ½” OD Return line (both made of stainless steel and with ¼” wall thicknesses). Using these sizes of pipe, the fluid velocities are about 27 ft/s in the Pressure line and 15 ft/s in the Return line, which are near the recommended values (higher velocities than these would require greater pumping power and would result in higher pressure losses and heat generation). In order to achieve the 0.76 Hz oscillation frequency needed to maintain the current testing speed, the flow capacity needs to be upgraded to about 280 – 300 GPM. Since the 505.150 is already one of the largest pumps on the market (it is a modular unit consisting of five separate 30 GPM pumps and can be upgraded slightly by adding one more) achieving this flow capacity will require using another pump in parallel with it. Fortunately, another 100 GPM pump already exists on the site, an MTS 506.72. After adding the extra 30 GPM module to the 505.150 to give it a 180 GPM capacity and combining it with the 506.72, the combined system will be able to supply the necessary 280 GPM flow.

Unfortunately, the addition of this second hydraulic power unit creates a number of problems – most notably in the amount of heat generation and in the flow speed of the oil. Clearly, if the flow rate of the oil is increased without increasing the size of the pipes being used, the velocity of the oil will also increase proportionately, as it follows the relation:

$$V = \frac{4Q}{\pi D^2} \tag{1}$$

where V is the velocity of the oil, Q is the volumetric flow rate of the oil, and D is the inner diameter of the pipe. If the existing pipes were used, the velocity of the oil in the Pressure line would be over 50 ft/s, which is far too high and would result in tremendous pressure losses at all of the bends and fittings, and could even cause the pipe to burst. Thus, to handle the increased flow, both the Pressure and Return lines (and the Drain line as well) must be resized.

To maintain the recommended flow velocities, it was calculated that the Pressure line's inner diameter needs to be approximately 3", while the Return line's needs to be almost 3 ½" (again, with ¼" wall thicknesses). However, stainless steel piping in these sizes is extremely expensive, while regular carbon steel piping generally does not provide the clean, smooth surfaces that are necessary for this type of precision application. (Any contaminants that the oil picks up from the pipe walls can damage the performance of the actuators.) Fortunately, a manufacturer (GS-Hydro) was found who produces piping in these sizes using carbon steel that has been treated with phosphate during production. According to the company, treating the steel with phosphate provides the smooth clean surface finish of stainless steel but without the associated cost [7]. Furthermore, all of their pipe segments are bolted and flanged together, rather than welded, thereby eliminating this costly procedure that can also add to the contaminants on the inside of the pipe. GS-Hydro also produces its own fittings and valves (and custom parts, if needed), which is another advantage. On the basis of the cost savings that result from using carbon steel, as well as the greater simplicity due to using non-welded parts that are all obtained from the same vendor, it was decided to buy the new piping components from GS-Hydro.

The second major problem that results from the addition of the second hydraulic power unit is the added heat generation. In order for the pump and the actuators to function properly, the temperature of the oil must be maintained below a certain critical level (in this case, around 100° F). If the oil temperature exceeds this level—which it naturally tends to do as it is being pumped and as it flows through all of the pipes and fittings—it can damage the actuators and the pump, and at the very least cause the actuators' sensors to function improperly. Therefore, in order to maintain the oil temperature at around 90°, an oil cooler must be incorporated into the system loop. In this situation, an air-cooled oil cooler (see Figure 3) is connected to the pump's reservoir, so that when the hot oil returns from the test section to the reservoir, it is sent outside to the oil cooler, which cools it down and returns it to the reservoir. In order to circulate the oil through this cooling loop, a small 5 hp sliding-vane rotary gear pump is used, located between the reservoir and the cooler. Also, in situations where no additional cooling is needed (such as when the pumps are operating at less than their maximum capacity), a thermostatic valve is included in the loop so that when the oil temperature is within the acceptable range it bypasses the cooler and simply returns to the reservoir.

The problem that arises when the second hydraulic power unit is added is that the amount of heat that is generated is simply too much for the one oil cooler to handle. The present model, a Young Radiator Company OCS 3000, is rated to reject a maximum of 800,000 Btu/hr (depending on the ambient temperature). According to the MTS literature, the maximum heat load for the 150 GPM pump is 765,000 Btu/hr. Thus, on warm days when the pump is operating at full capacity, the cooler is already pushing the limits of what it can handle. When the system's capacity is increased to 280 GPM this oil cooler will simply not be able to handle the heat load (which could then reach as high as 1.5 MBtu/hr) and a second cooler—and possibly even a third—will become necessary. After a bit of hunting, a new oil cooler was found (an American Industrial Heat Transfer AOCS-3015) which is almost identical to the existing cooler and costs about $4,000 less ($9,000 versus $13,000).

This new cooler will be installed next to the present one, with the line from the reservoir splitting the flow of oil between the two so that they operate in parallel, doubling the system's cooling capacity. But in order to do this, the pumping capacity of the circulation pump—which is currently 100 GPM—must also be doubled. Fortunately, rather than having to buy a whole new pump, this can be done simply by installing a larger motor (10 hp vs. 5 hp) and using a different gear reducer between the motor and the pump. This upgrade to the circulation pump is being done by Eaton Sales and will cost approximately $2,000. However, like with the oil flowing to the actuators, when the flow capacity to the coolers is doubled, the pipe sizes must also be increased—from 2" to 3" lines. This in turn requires that a new 3" hydrostatic valve be purchased and this component costs about $900. Additionally, in order to ensure that the hot oil from both of the major pumps is cooled equally (rather than having the circulation pump drawing all of its oil from one pump and letting the other remain hot), a reservoir commoning tank will be added to the hydraulics room between the two pumps. In this arrangement, a 6" line will connect both reservoirs to this tank and the circulation pump will draw its oil from this tank via a 3" gravity-fed line. Of course, the oil returning from the cooler will be sent directly back to the two main reservoirs.

- **Implementing the Upgrade**

When all is said and done, the entire hydraulics system upgrade will require tearing out all of the existing piping from the hydraulics room to the actuators in the test section and to the cooler and installing larger piping; installing a new cooler; replacing the motor and the gear reducer on the circulation pump; installing a new hydrostatic valve; as well as removing the air compressor from the hydraulics room and moving the 100 GPM pump into the room. When this entire process is complete, the layout of the room will look quite different, as Figures 4 and 5 show.

At this time, it is estimated that the entire upgrade will cost about $62,000, as indicated in Table 1 below. However, because the amount originally budgeted for the project was only $30,000, the project will probably have to be completed in phases, as additional funds become available. Thus it may take a while for the entire upgrade to be completed. Even if all of the necessary money were currently available though, due to the size and the nature of these components, this project would take at least a month or two to complete and have all of the new equipment running properly.

Table 1. Hydraulics System Upgrade Bill of Materials

Item Description	Approximate Cost
Oil Cooler	$9,226
AMOT Thermostatic valve	$880
New Piping (GS-Hydro)	$50,000
-- Pressure-side piping	($40,000)
-- Cooling-side piping	($5,000)
---- Pump commoning	($5,000)
Circ Pump Upgrade	$2,000
TOTAL:	**$62,106**

Ultimately, the total capacity of the hydraulic oil delivery system will be increased substantially—about 87%, from 150 GPM to 280 GPM, and maybe even more at some point in the future. When this is done, the NWTC will again be able to say that it is one of the most advanced structural testing facilities in the world, and will continue to be able to support the growth and development of the U.S. wind industry. As a result of over 20 years of research and innovation, wind energy technology has advanced to the point that the wind turbines now being produced are so large and so robust that they are stretching the limits of the equipment used in testing them. The fact that these test facilities at the IUF that the industry has out-grown are only five years old illustrates just how rapidly wind energy technology is developing. Thus, although this project will certainly not be inexpensive or simple, in order to encourage this continued growth and to enable wind energy to become increasingly competitive with conventional energy sources, this facilities upgrade must take place.

Acknowledgements

I would first like to thank the Department of Energy's Office of Science and the National Renewable Energy Laboratory for giving me the opportunity to take part in the Energy Research Undergraduate Laboratory Fellowships program here this summer. I would also like to express my gratitude to my mentor, Walt Musial, and to Scott Hughes and the rest of the staff here at the National Wind Technology Center for their excellent guidance and support this summer.

References

[1] "U.S. Energy Consumption By Source, 1995." Factmonster.com. Accessed on July 5, 2001. **http://www.factmonster.com/ipka/A0775710.html**

[2] "2001 Wind Energy Across America Calendar." U.S. Department of Energy Wind Program. January 2001.

[3] "Research to Expand Our Energy Supply." Wind Power Today. U.S. Department of Energy, Office of Scientific and Technical Information. May 2001.

[4] "U.S. Electricity Production Costs." Nuclear Energy Institute (1999). Accessed on July 20, 2001.
http://www.nei.org/documents/Line_Graph_US_Electricity_Production_Costs_1981_to_1999.pdf

[5] "Operation and Maintenance Costs for Wind Turbines." Danish Wind Turbine Manufacturers Association (2000). Accessed on July 21, 2001.
http://www.windpower.dk/tour/econ/oandm.htm

[6] "Testing Wind Turbine Rotor Blades." Danish Wind Turbine Manufacturers Association (2000). Accessed on July 21, 2001.
http://www.windpower.dk/tour/manu/bladtest.htm

[7] "Piping Without Welding." GS-Hydro Product Overview Brochure (2000). Powell Print, Inc., Dover, UK.

Figures

Figure 1. The MTS 505.150/180 Hydraulic Power Unit (HPU) that currently exists in the IUF Hydraulics room.

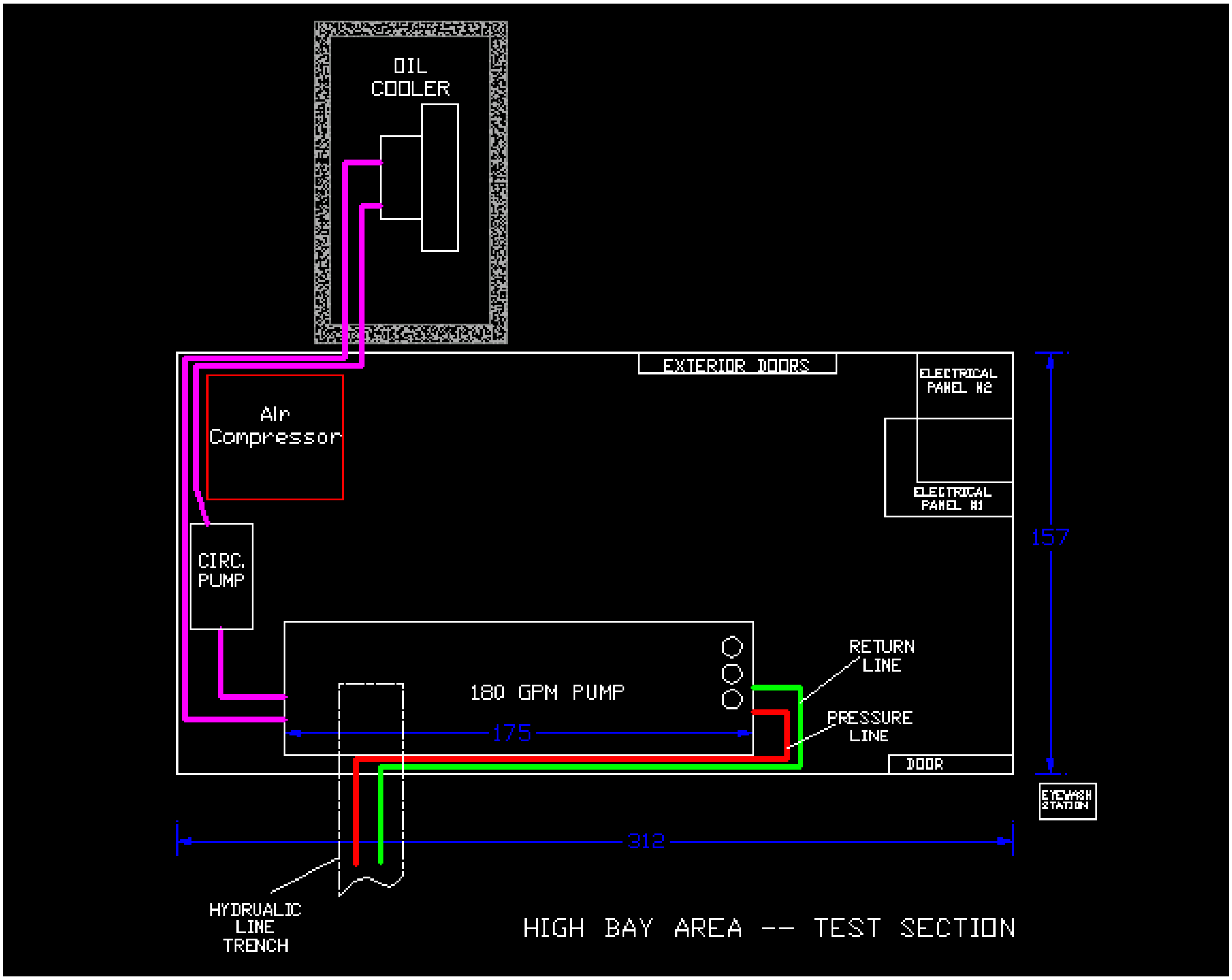

Figure 2. Current layout of the IUF's Hydraulic room, showing the contents of the room, the oil cooler located outside, and the High Bay testing area adjacent to the room.

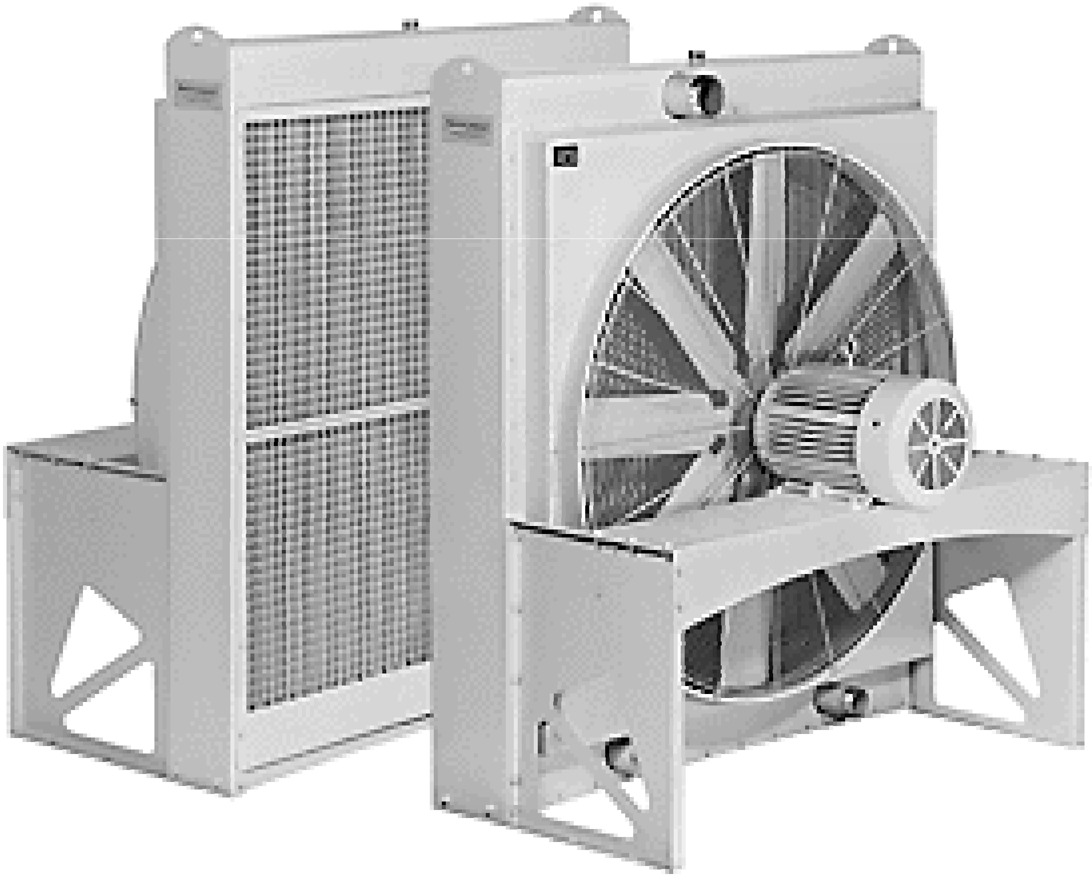

Figure 3. American Industrial Heat Transfer Inc.'s AOCS-3015 air-cooled oil cooler.

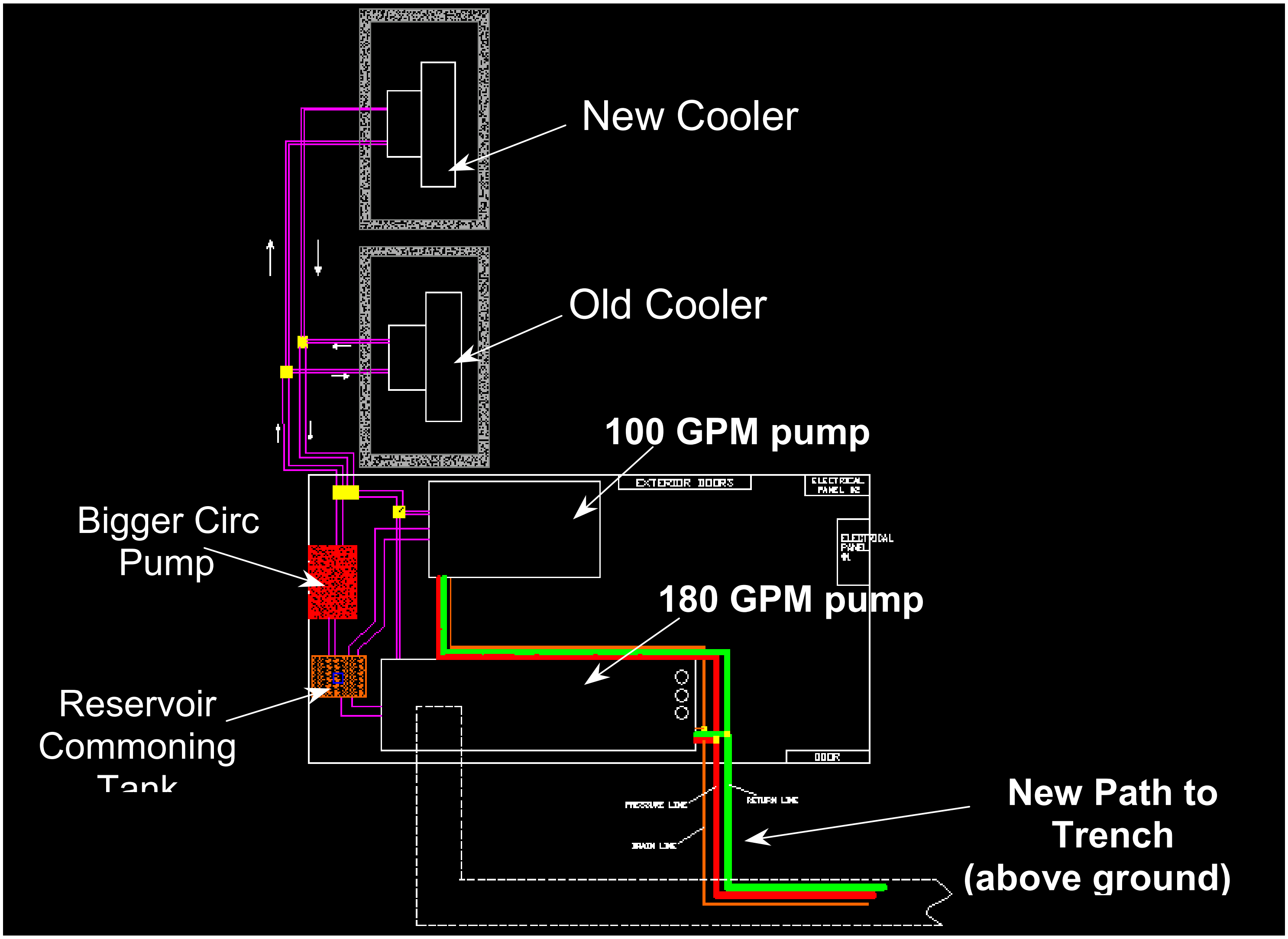

Figure 4. Possible future layout of IUF Hydraulics room, featuring a new above ground path for the hard lines from the pumps to the trenches.

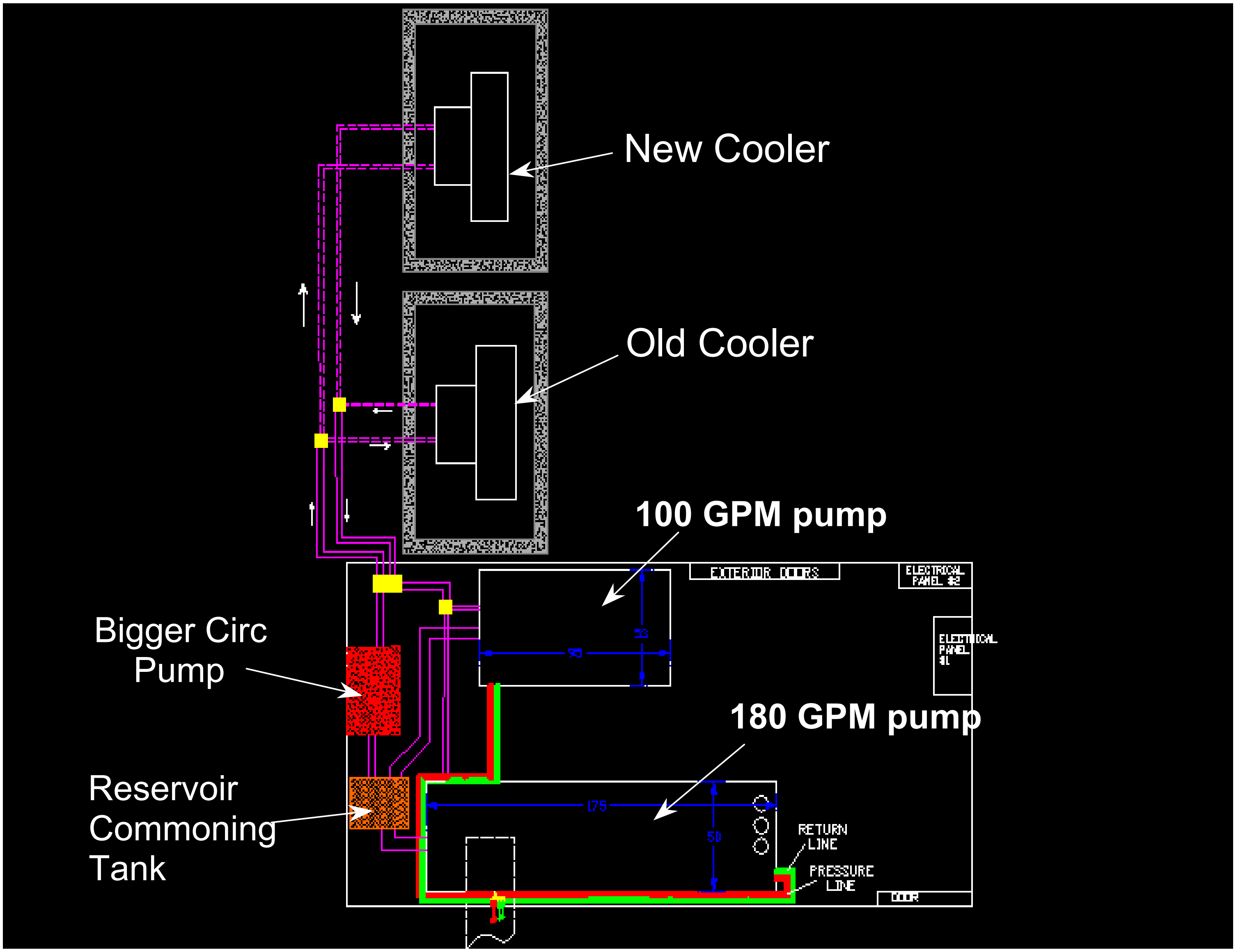

Figure 5. Another possible future layout for the IUF Hydraulics room, utilizing the existing pathway for the hardlines between the pumps and the trenches.